An Abrasion-Ablation Model Description of Galactic Heavy-Ion Fragmentation

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INTRODUCTION

As the era of the Space Transportation System progresses, and the possibility of a permanent manned presence in space unfolds, the necessity for improved radiation protection methods, for career astronauts who will spend appreciable periods of time in the space environment, increases in significance (ref. 1). The combination of long-duration missions and career astronauts will cause the high-energy heavy-ion (HZE) component of galactic cosmic rays to assume major radiobiological significance, especially for cumulative damage to nonregenerative tissues (ref. 2) and latent carcinogenesis (ref. 3). The greater ranges of these particles, when compared with typical thicknesses of spacecraft walls, suggest that nuclear attenuation and fragmentation may provide the only viable means of protection. Unfortunately, the secondary radiations produced by these galactic cosmic rays as they fragment also include HZE particles, so that appreciable thicknesses of bulk material may not substantially reduce the transmitted doses (ref. 3). As a result, HZE particle shielding may prove to be impractical for space applications. The need remains, however, to develop an accurate fragmentation theory in order to adequately assess the effects of fragmentation by existing spacecraft structure and human body mass on the doses received by critical organs of interest. Alternatives to passive shielding methods, such as using electromagnetic fields as HZE particle shields, do not appear to be technologically (ref. 4) or economically feasible (ref. 5). However, no detailed study of their possible application to the entire spectrum of space radiations has yet been performed.

In this work, a simple theory of HZE fragmentation based upon a two-step abrasion-ablation model is presented. For the abrasion step, a quantum-mechanical formalism based upon an optical model potential approximation to the exact nucleus-nucleus multiple-scattering series is used (refs. 6 to 9). The charge dispersions of the excited projectile prefragments (the pieces of projectile nuclei remaining immediately after the abrasions) are calculated using both a hypergeometric distribution and a method based upon the zero-point oscillations of the giant dipole resonance (ref. 10). The prefragment excitation energies are estimated from the geometric "clean-cut" abrasion-ablation model of Bowman, Swiatecki, and Tsang (ref. 11). The ablation part of the fragmentation process is analyzed by calculating compound nucleus decay probabilities for the various particle emission channels using the Monte Carlo program EVAP-4, developed at Oak Ridge National Laboratory (ref. 12). Finally, to illustrate the theory, theoretical predictions of elemental production cross sections for 1.88-GeV/nucleon iron projectiles colliding with stationary target nuclei of carbon, silver, and lead are made and compared with experimental data (ref. 13) and with the predictions from the semiempirical relations of Silberberg et al. (ref. 14).

FRAGMENTATION THEORY

In the abrasion-ablation fragmentation model, the projectile nuclei, moving at relativistic speeds, collide with stationary target nuclei. In the abrasion step, those portions of the nuclear volumes which overlap are sheared away by the collision. The remaining projectile piece, called a prefragment or primary residue, continues its trajectory with essentially its precollision velocity. As a result of the dynamics of the abrasion process, the prefragment is highly excited and subsequently

decays by the emission of gamma radiation and/or nuclear particles. This step is the ablation stage. The resultant isotope, sometimes referred to as a secondary product, is the nuclear fragment whose cross section is measured. The abrasion process can be analyzed using classical geometric arguments (refs. 11 and 15) or methods obtained from formal quantum scattering theory (refs. 6 to 9 and 16). The ablation stage can be analyzed from geometric arguments (ref. 11) or more sophisticated methods based upon Monte Carlo or intranuclear cascade techniques (refs. 10, 12, 15, and 16). Predictions of fragmentation cross sections can also be made using the approximate, semiempirical, parameterization formulas of Silberberg et al. (ref. 14).

Abrasion Cross Sections

From reference 9, the cross section for abrading m projectile nucleons is

$$\sigma_m = \binom{A_P}{m} \int d^2\vec{b} \left[1 - P(\vec{b}) \right]^m P(\vec{b})^{A_F} \tag{1}$$

where $P(\vec{b})$ is the probability, as a function of impact parameter, for not removing a nucleon in the collision and A_F, the residual mass (prefragment) number, is

$$A_F = A_P - m \tag{2}$$

Within the context of eikonal scattering theory, an optical model potential approximation to the exact nucleus-nucleus multiple-scattering series, which includes Pauli correlation effects, yields (ref. 9)

$$P(\vec{b}) = \exp\left[-A_T \sigma(e) I(\vec{b}) \right] \tag{3}$$

with

$$I(\vec{b}) = \left[2\pi B(e) \right]^{-3/2} \int dz_0 \int d^3\vec{\xi}_T \rho_T(\vec{\xi}_T) \int d^3\vec{y} \, \rho_P(\vec{b} + \vec{z}_0 + \vec{y} + \vec{\xi}_T)$$

$$\times \exp\left[-y^2/2B(e) \right]\left[1 - C(\vec{y}) \right] \tag{4}$$

(A list of symbols and abbreviations used in this paper appears after the references.) Methods for determining the appropriate nuclear distributions ρ_i ($i = P,T$) and constituent-averaged nucleon-nucleon cross sections $\sigma(e)$ are described in reference 17. Values for the nucleon-nucleon scattering slope parameter are obtained from the parameterization, appropriate for diffractive scattering, given in reference 18. From reference 9, the Pauli correlation is

$$C(\vec{y}) = 0.25 \exp\left(-k_F^2 y^2/10 \right) \tag{5}$$

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where

$$k_F = 1.36 \ fm^{-1}$$

Prefragment Charge Distributions

Since the abraded nucleons consist of protons and neutrons, which are not identical, a prescription for calculating the charge dispersions of the prefragments is needed in order to calculate final, isotope, and/or elemental production cross sections caused by the fragmentation process. Two such methods are used in the fragmentation theory described in this work. The first method (ref. 19) treats the neutron and proton distributions as completely uncorrelated. The cross section for forming a particular prefragment of mass A_j and charge z_j is then given in terms of the cross section for abrading m nucleons σ_m as

$$\sigma_{abr}(Z_j, A_j) = \frac{\binom{N}{n}\binom{Z}{z}}{\binom{A_P}{m}} \sigma_m \tag{6}$$

where z out of the original Z projectile nucleus protons are abraded along with n out of the original N projectile neutrons. Note that

$$A_P = N + Z \tag{7}$$

and

$$m = n + z \tag{8}$$

with

$$Z_j = Z - z \tag{9}$$

and

$$A_j = A_P - m \tag{10}$$

The hypergeometric distribution is based on the assumption that there is no correlation at all between neutron and proton distributions. Therefore, unphysical results such as abrading all neutrons or protons from a nucleus while leaving the remaining fragment intact could occur.

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As an alternative to the hypergeometric distribution, Morrissey et al. (ref. 10) proposed a charge dispersion model based upon the zero-point vibrations of the giant dipole resonance of the projectile nucleus. In this model, equation (6) becomes

$$\sigma_{abr}(Z_j, A_j) = N_j \left(2\pi\alpha_Z^2\right)^{-1/2} \exp\left\{\frac{-\left[Z_j - A_j(Z/A_P)\right]^2}{2\alpha_Z^2}\right\} \sigma_m \tag{11}$$

where the variance (dispersion) is

$$\alpha_Z = 2.619(u/A_P)^{1/2}(Z/A_P)(dm/db)(1 + u)^{-3/4} \tag{12}$$

with

$$u = \frac{3J}{Q(A_P)^{1/3}} \tag{13}$$

In the droplet model of the nucleus, the coefficients J and Q have the nominal values of 25.76 MeV and 11.9 MeV, respectively (ref. 10). The rate of change of the number of nucleons removed as a function of impact parameter (dm/db) is calculated numerically using the geometric abrasion model of reference 10. The normalization factor N_j insures that for a given value of A_j, the discrete sum over all allowed values of Z_j yields unity for the dispersion probabilities. This overall normalization is a new feature of this work and is not included in the original model of reference 10.

Prefragment Excitation Energies

The excitation energy of the projectile prefragment following abrasion of m nucleons is calculated from the clean-cut abrasion formalism of references 11 and 15. For this model, the colliding nuclei are assumed to be uniform spheres of radii R_i $(i = P, T)$. In the collision, the overlapping volumes shear off so that the resultant projectile prefragment is a sphere with a cylindrical hole gouged out of it. The excitation energy is then determined by calculating the difference in surface area between the misshapen sphere and a perfect sphere of equal volume. This excess surface area Δ is given by (ref. 15)

$$\Delta = 4\pi R_P^2 \left[1 + P - (1 - F)^{2/3}\right] \tag{14}$$

where the expressions for P and F differ depending upon the nature of the collision (peripheral versus central) and the relative sizes of the colliding nuclei.

For the case where $R_T > R_P$, we have (ref. 15)

$$P = 0.125(\mu\nu)^{1/2}\left(\frac{1}{\mu} - 2\right)\left(\frac{1 - \beta}{\nu}\right)^2 - 0.125\left[0.5(\mu\nu)^{1/2}\left(\frac{1}{\mu} - 2\right) + 1\right]\left(\frac{1 - \beta}{\nu}\right)^3 \tag{15}$$

and

$$F = 0.75(1 - \nu)^{1/2}\left(\frac{1 - \beta}{\nu}\right)^2 - 0.125\left[3(1 - \nu)^{1/2} - 1\right]\left(\frac{1 - \beta}{\nu}\right)^3 \tag{16}$$

with

$$\nu = \frac{R_P}{R_P + R_T} \tag{17}$$

$$\beta = \frac{b}{R_P + R_T} \tag{18}$$

and

$$\mu = \frac{1}{\nu} - 1 = \frac{R_T}{R_P} \tag{19}$$

Equations (15) and (16) are valid when the collision is peripheral (i.e., the two nuclear volumes do not completely overlap). In this case, the impact parameter b is restricted such that

$$R_T - R_P \leqslant b \leqslant R_T + R_P \tag{20}$$

If the collision is central, then the projectile nucleus volume completely overlaps the target nucleus volume ($b < R_T - R_P$), and all the projectile nucleons are abraded. In this case, equations (15) and (16) are replaced by

$$P = -1 \tag{21}$$

and

$$F = 1 \tag{22}$$

and there is no ablation of the projectile, since it was destroyed by the abrasion.

For the case where $R_P > R_T$ and the collision is peripheral, equations (15) and (16) become (ref. 10)

$$P = 0.125(\mu\nu)^{1/2}\left(\frac{1}{\mu} - 2\right)\left(\frac{1 - \beta}{\nu}\right)^2 - 0.125\left\{0.5(\nu/\mu)^{1/2}\left(\frac{1}{\mu} - 2\right)\right.$$

$$\left. - \frac{[(1/\nu)(1 - \mu^2)^{1/2} - 1][(2 - \mu)\mu]^{1/2}}{\mu^3}\right\}\left(\frac{1 - \beta}{\nu}\right)^3 \tag{23}$$

and

$$F = 0.75(1 - \nu)^{1/2}\left(\frac{1 - \beta}{\nu}\right)^2 - 0.125\left\{\frac{3(1 - \nu)^{1/2}}{\mu}\right.$$

$$\left. - \frac{[1 - (1 - \mu^2)^{3/2}][1 - (1 - \mu)^2]^{1/2}}{\mu^3}\right\}\left(\frac{1 - \beta}{\nu}\right)^3 \tag{24}$$

where the impact parameter is restricted such that

$$R_P - R_T \leqslant b \leqslant R_P + R_T \tag{25}$$

For a central collision ($b < R_P - R_T$) with $R_P > R_T$, equations (23) and (24) become

$$P = \left[\frac{1}{\nu}(1 - \mu^2)^{1/2} - 1\right]\left[1 - \left(\frac{\beta}{\nu}\right)^2\right]^{1/2} \tag{26}$$

and

$$F = \left[1 - (1 - \mu^2)^{3/2}\right]\left[1 - \left(\frac{\beta}{\nu}\right)^2\right]^{1/2} \tag{27}$$

For the excess surface area obtained from equation (14), the excitation energy is given by

$$E_{exc} = \Delta \cdot E_s \tag{28}$$

where E_s, the nuclear surface energy coefficient (refs. 11 and 15) obtained from the liquid drop model of the nucleus, is 0.95 MeV/fm^2

Ablation Factors

Depending upon the excitation energy, the excited prefragment may decay by emitting one or more nucleons (protons or neutrons), composites (deuterons, tritons, ^{3}He, or alpha particles), or gamma rays. The probability α_{ij} for formation of a particular final fragment of type i as a result of the deexcitation of a prefragment of type j is obtained from the EVAP-4 computer code (ref. 12) by treating the prefragment as a compound nucleus with an excitation energy given by equation (28). The final fragmentation cross section for production of the type-i isotope is then given by

$$\sigma_F(Z_i, A_i) = \sum_j \alpha_{ij} \; \sigma_{abr}(Z_j, A_j) \tag{29}$$

where $\sigma_{abr}(Z_j, A_j)$ is obtained from equation (6) or equation (11). The elemental production cross sections are obtained by summing over all isotope contributions as

$$\sigma_F(Z) = \sum_A \sigma_F(Z, A) \tag{30}$$

FRAGMENTATION RESULTS

As an illustrative application of the theory, element production cross sections for fragments of calcium (Z = 20) and heavier elements were calculated for ^{56}Fe projectiles, at 1.88 GeV/nucleon incident kinetic energy and collided with stationary target nuclei of ^{12}C, ^{108}Ag, and ^{208}Pb. These reactions were chosen for analyses because of the availability of experimental data for comparison purposes (ref. 13) and because relativistic ^{56}Fe nuclei are among the dominant HZE particles of radiobiological significance for manned spaceflight (ref. 2).

Tables I through III display the elemental production cross sections obtained for carbon, silver, and lead targets using both the hypergeometric (eq. (6)) and giant dipole resonance (eq. (11)) dispersion expressions. Also displayed are the experimental results from Lawrence Berkeley Laboratory (ref. 13). Except for the cross sections for Mn production (carbon and silver targets) and V production (silver and lead targets), the agreement between theory and experiment is quite good. When compared with the predictions obtained with the hypergeometric distribution assumption of equation (6), the use of the giant dipole resonance expression for charge dispersion (eq. (11)) appears to yield slightly improved overall agreement between theory and experiment.

Figures 1 through 3 display the elemental production cross sections obtained from equation (11), for the giant dipole resonance dispersion, along with the experimental data from reference 13. Also displayed, for comparison, are the predictions from the semiempirical relations of Silberberg et al. (ref. 14). For the semiempirical relations, the unmodified predictions are displayed. Also displayed are the fragmentation cross sections obtained by renormalizing to insure mass and charge conservation. Details of the renormalization can be found in reference 20. For the

carbon target (ref. 21), χ^2 for the giant dipole resonance (GDR) predictions is 31.6, which is larger than the 19.4 obtained using the Silberberg-Tsao (ST) methods. For the GDR, most of the χ^2 comes from the Mn overestimate. If that point is excluded, χ^2 is reduced from 31.6 to 9.4. The comparative results for Ca, Sc, Ti, V, and Cr are in better agreement with experiment. For the silver target, the GDR χ^2 is 57.3 (5.2 if the Mn datum is excluded), whereas the ST χ^2 is 32.4 (9.5 if the Mn datum is excluded). For the lead target, the GDR χ^2 is 4.4 (1.9 if the V datum is excluded), compared with the ST χ^2 of 52.4 (2.3 if the Mn underestimate is excluded). In general, the overall agreement between theory and experiment for the abrasion-ablation model is satisfactory considering its simple nature.

In previous heavy-ion transport work (refs. 22 and 23), it was demonstrated that the improved agreement between theory and experiment for Bragg (depth-dose) curves was obtained by using Silberberg-Tsao fragmentation parameters modified to scale by velocity (rather than total kinetic energy) and renormalized to conserve fragment charge and mass. As shown in figures 1 through 3, the modifications (labeled VR) do improve the ST predictions for the predominate, near-projectile mass fragments (in this case, Mn), but yield substantial overestimates for the fragmentation cross sections for the lighter mass fragments. Simple corrections to the Silberberg-Tsao parameters, such as renormalization, are apparently adequate for gross total-dose comparisons (ref. 23). However, only certain fragments may be biologically signifi- cant (ref. 3). Therefore, these corrections may be inadequate for the more pertinent shielding problems such as the accurate prediction of individual fragment species production. Clearly, the need remains for a comprehensive and accurate HZE particle fragmentation theory, of which the work described herein is a beginning.

Future improvements to this simple abrasion-ablation model will center on extending the GDR charge dispersion method to incorporate the actual quantum- mechanical abrasion formalism rather than using the geometric model approximation of reference 10. Improved methods for estimating the prefragment excitation energy spectrum will also be developed. Finally, if necessary, an alternative to the EVAP-4 ablation code will be tried, such as an intranuclear cascade code (ref. 24); or the development of other methods to describe the ablation step will be undertaken.

CONCLUDING REMARKS

A simple abrasion-ablation model for describing the nuclear fragmentation of galactic heavy ions has been presented. The model was shown to yield reasonable agreement with experimental elemental production cross sections. These cross sec- tions were obtained at the Lawrence Berkeley Laboratory for the fragmentation of relativistic ion nuclei by various targets. Comparisons were also made with predic- tions obtained from the semiempirical formulation of Silberberg and co-workers. Simple corrections to the latter, such as the mass and charge renormalization which previously yielded improved estimates for total radiation dose as a function of depth in an extended water column, were shown to be inadequate for accurately predicting individual fragmentation cross sections.

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<center>SYMBOLS</center>

A	nuclear mass number
A_T	target nuclear mass number
B(e)	average slope parameter of nucleon-nucleon scattering amplitude, fm^2
b	projectile impact parameter, fm
$C(\vec{y})$	Pauli correlation function, defined in equation (5)
E_{exc}	projectile prefragment excitation energy, MeV
E_s	nuclear surface energy coefficient, MeV
e	two-nucleon kinetic energy in their center of mass frame, GeV
F	function defined in equations (16), (22), (24), and (27)
GDR	giant dipole resonance
$I(\vec{b})$	defined in equation (4)
J	droplet model coefficient (25.76 MeV)
m	number of abraded nucleons
N	total number of nuclear neutrons
N_j	renormalization coefficient for jth prefragment
n	number of abraded neutrons
P	function defined in equations (15), (21), (23), and (26)
$P(\vec{b})$	probability for not removing a single nucleon by abrasion
Q	droplet model coefficient (11.9 MeV)
R_P	uniform nuclear radius of projectile, fm
R_T	uniform nuclear radius of target, fm
ST	predictions of Silberberg-Tsao formulation without renormalization
u	defined in equation (13)
VR	predictions of Silberberg-Tsao formulation with renormalization
y	two-nucleon relative position, fm
Z	total number of nuclear protons
z	number of abraded protons

z_o longitudinal position of projectile center of mass, fm

$\binom{A}{m}$ binomial coefficient

α_{ij} probability of formation of type-i fragment as a result of deexcitation of type-j fragment

α_Z defined in equation (12)

β defined in equation (18)

Δ excess nuclear surface area, fm^2

μ defined in equation (19)

ν defined in equation (17)

ξ_T collection of constituent relative coordinates for target, fm

ρ nuclear density, fm^{-3}

ρ_P projectile nuclear density, fm^{-3}

ρ_T target nuclear density, fm^{-3}

$\sigma(e)$ average nucleon-nucleon total cross section, mb

$\sigma_{abr}(Z,A)$ cross section for production of nucleus of type (Z,A) by abrasion, mb

σ_F fragmentation cross section, mb

σ_m cross section for abrading m nucleons, mb

An arrow over a symbol denotes a vector.

TABLE I.- ELEMENTAL PRODUCTION CROSS SECTIONS FOR THE REACTION
$$^{56}Fe + {}^{12}C \rightarrow Z + X$$

[Incident kinetic energy is 1.88 GeV/nucleon]

Element produced	Elemental production cross sections, mb		
	Hypergeometric	Giant dipole resonance	Experiment (ref. 13)
Fe	161	209	
Mn	321	308	181 ± 27
Cr	156	142	124 ± 13
V	126	124	100 ± 11
Ti	90	88	87 ± 11
Sc	69	69	54 ± 9
Ca	77	78	78 ± 11

TABLE II.- ELEMENTAL PRODUCTION CROSS SECTIONS FOR THE REACTION
$$^{56}Fe + {}^{108}Ag \rightarrow Z + X$$

[Incident kinetic energy is 1.88 GeV/nucleon]

Element produced	Elemental production cross sections, mb		
	Hypergeometric	Giant dipole resonance	Experiment (ref. 13)
Fe	296	262	
Mn	381	446	280 ± 23
Cr	226	230	218 ± 21
V	150	149	117 ± 15
Ti	126	128	124 ± 16
Sc	101	100	104 ± 13
Ca	102	112	118 ± 14

TABLE III.- ELEMENTAL PRODUCTION CROSS SECTIONS FOR THE REACTION
$^{56}Fe + {}^{208}Pb \rightarrow Z + X$

[Incident kinetic energy is 1.88 GeV/nucleon]

Element produced	Elemental production cross sections, mb		
	Hypergeometric	Giant dipole resonance	Experiment (ref. 13)
Fe	345	302	
Mn	445	521	509 ± 40
Cr	267	268	242 ± 25
V	175	174	142 ± 20
Ti	152	151	148 ± 22
Sc	121	119	111 ± 17
Ca	116	129	144 ± 22
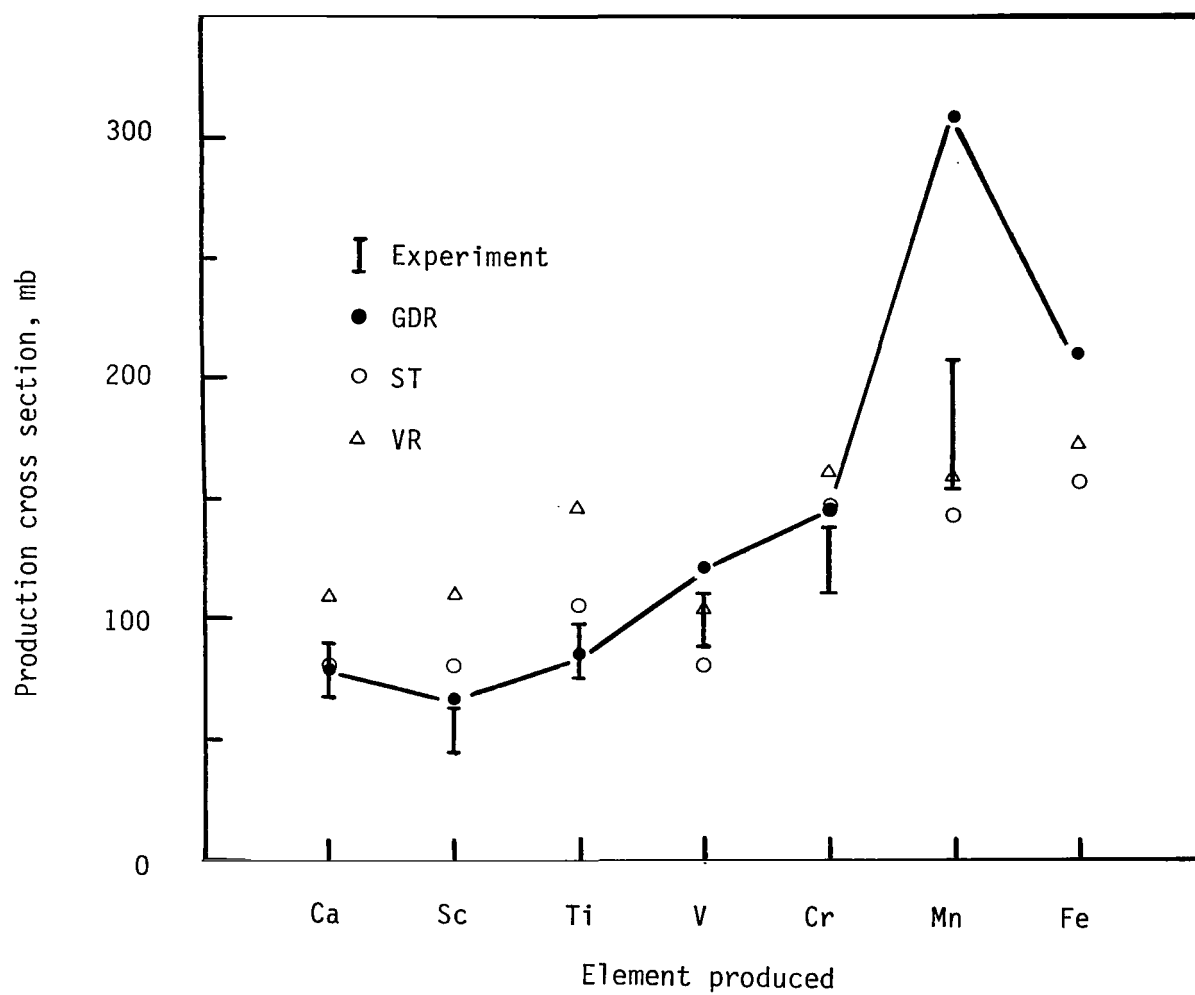
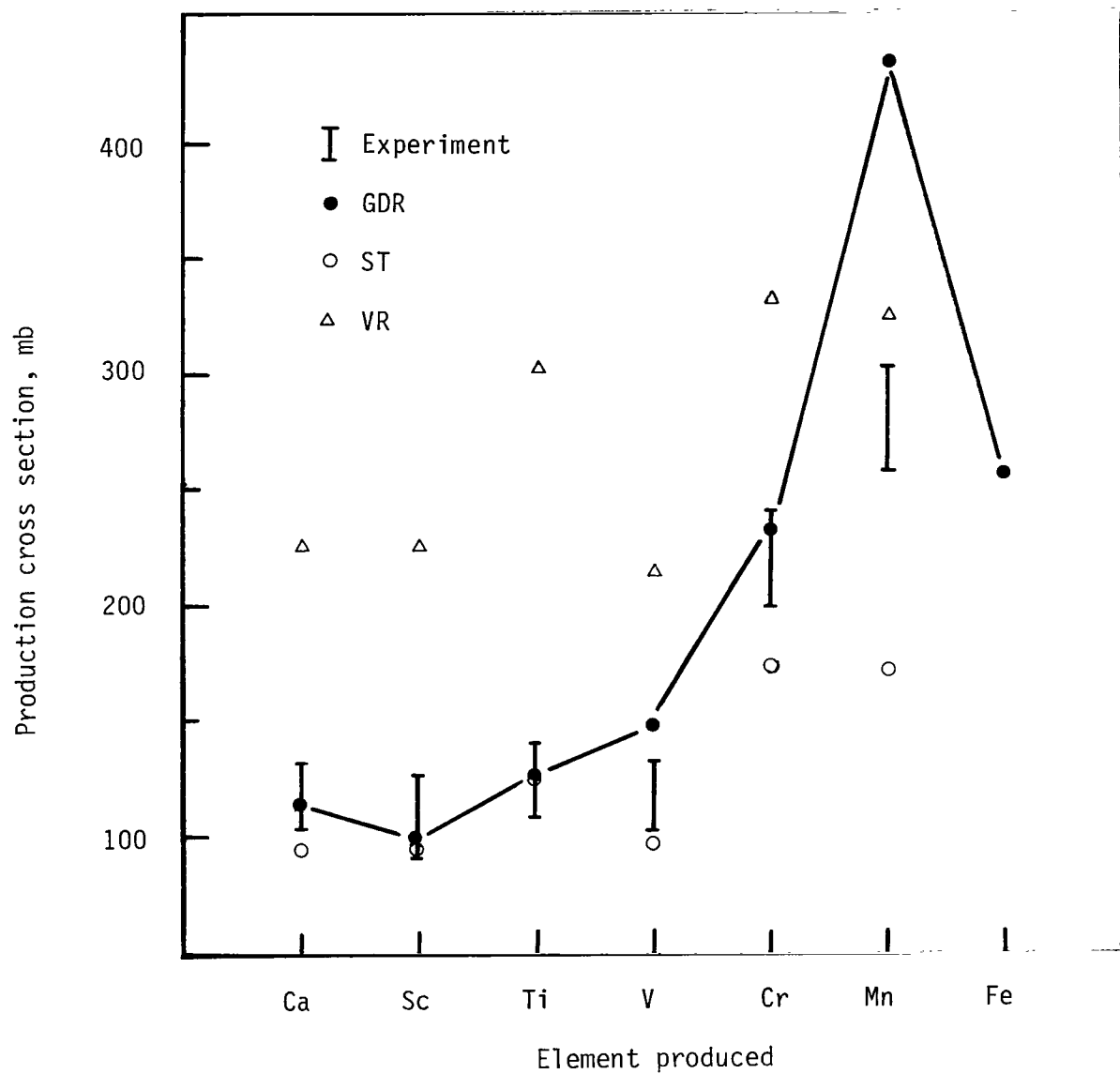Figure 1.- Elemental production cross sections for iron projectile nuclei fragmenting in carbon targets.

Figure 2.- Elemental production cross sections for iron projectile nuclei fragmenting in silver targets.
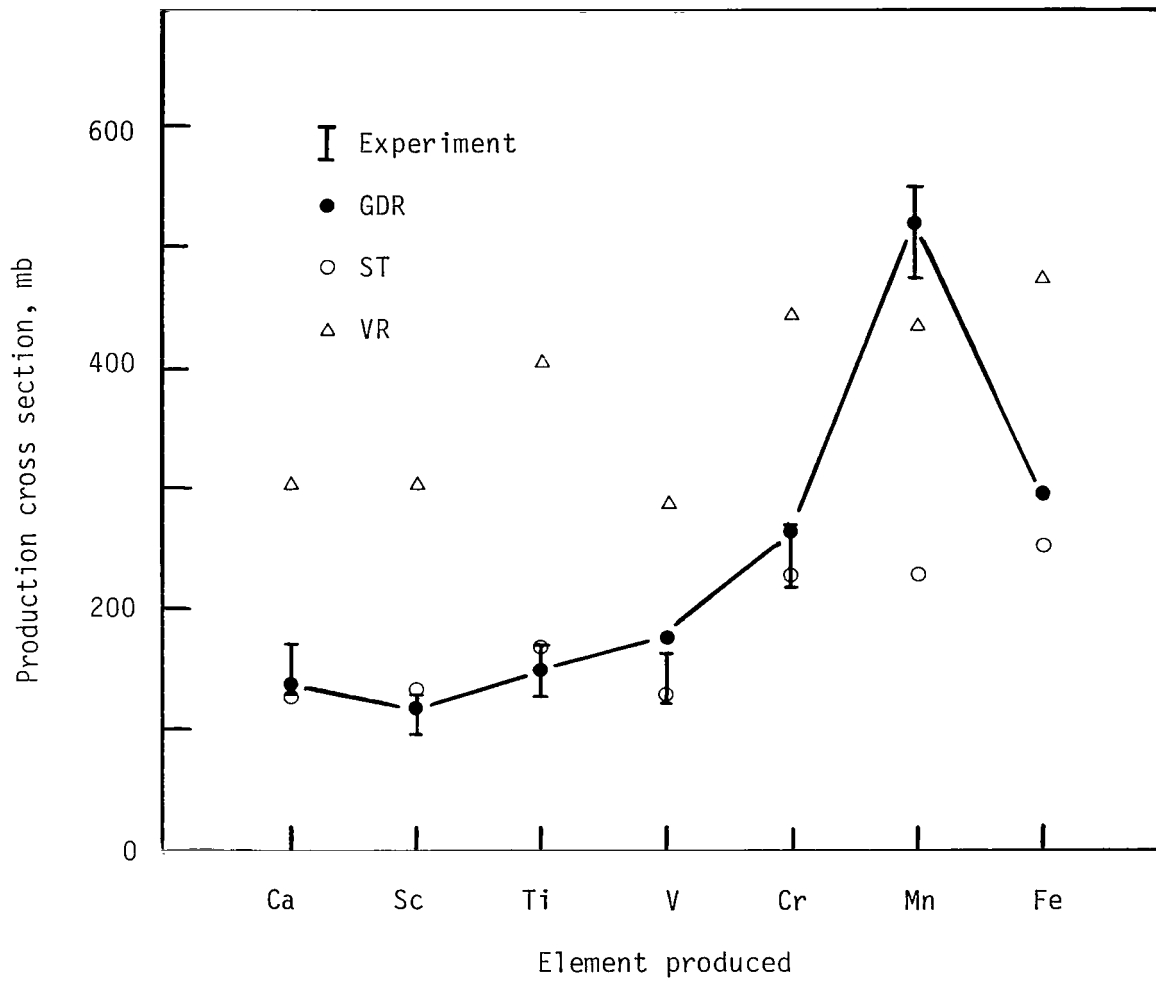
Figure 3.- Elemental production cross sections for iron projectile nuclei fragmenting in lead targets.

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15. Supplementary Notes

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16. Abstract

The fragmentation of high-energy galactic heavy ions by nuclear interactions with arbitrary target nuclei is described within the context of a simple abrasion-ablation fragmentation model. The abrasion part of the theory utilizes a quantum-mechanical formalism based upon an optical model potential approximation to the exact nucleus-nucleus multiple-scattering series. Nuclear charge distributions of the excited prefragments are calculated using either a hypergeometric distribution or a method based upon the zero-point oscillations of the giant dipole resonance. The excitation energy of the prefragment is estimated from the geometric "clean-cut" abrasion-ablation model. The decay probabilities for the various particle emission channels, in the ablation stage of the fragmentation, are obtained from the EVAP-4 Monte Carlo computer program. Elemental production cross sections for 1.88-GeV/nulceon iron colliding with carbon, silver, and lead targets are calculated and compared with experimental data and with the predictions from the semiempirical relations of Silberberg and Tsao.

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